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## HIGH-EFFICIENCY FUEL PROCESSOR VIA STEAM INTEGRATION FROM A WATER-COOLED STACK

### BACKGROUND OF THE INVENTION

**[0001]** The present invention relates generally to small-scale, highly integrated fuel cell systems and particularly, to improving fuel processor efficiency via steam integration from a water-cooled high temperature fuel cell stack.

**[0002]** A typical fuel cell system includes a fuel processor, a combustor, and a fuel cell stack to generate electricity useful for transportation and power generation applications. The typical fuel processor uses three steps to convert a liquid fuel, such as gasoline or methanol, or a gaseous fuel, such as methane, into a hydrogen-rich gaseous reformat that can be used to make electricity in the fuel cell stack. In the first step, the primary reactor (usually an auto thermal reactor (ATR) or steam reformer (SR)) converts the fuel to the gaseous reformat, but with significant (6% to 10%) carbon monoxide (CO). In the second step, a water-gas-shift reactor (WGS) is typically used to reduce the CO to 0.3% to 1% and increase the hydrogen content in the gaseous reformat. The final step is accomplished typically with either a partial oxidation (PrOx) reactor or a pressure-swing adsorption (PSA) device. In this step, the remaining CO present in the gaseous reformat is further reduced to about 2 to 50 part per million (ppm), depending on the fuel cell stack used.

**[0003]** The combustor is typically included in the fuel cell system to clean up residual methane and hydrogen that exits the fuel cell stack. Heat from the combustor is used to generate steam

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for the ATR and WGS reactors and in some cases, heat from the PrOx reactor may also be used for steam generation. The steam, and in some cases fuel and air is superheated via either the combustor heat or the heat from the gaseous reformat between the ATR and WGS reactors.

**[0004]** Current conventional proton exchange membrane fuel cell (PEMFC) stacks typically operate at about 60° C to about 90° C, but new PEMFC stacks currently being developed will operate at much higher temperatures, such as for example, about 100° C to 150° C. These high temperature PEMFC stacks will offer several advantages over conventional PEMFC stacks including easier stack heat rejection and greater CO tolerance. CO tolerance for a stack temperature of 100 to 150 C is estimated to be about 0.03% to about 0.5%. Additionally, further efficiency can be achieved in such fuel cell systems if the surplus heat produced by system components is utilized. Accordingly, there is a continued need to achieve higher overall system efficiencies in small-scale, highly integrated fuel cell systems.

#### SUMMARY OF THE INVENTION

**[0005]** The present invention meets the above-mentioned need by providing a new source of steam generation for a fuel processor in a fuel cell system utilizing water vaporization cooling for a high temperature fuel cell stack. In particular, a portion of the steam generated from water used to cool the high temperature fuel cell stack is re-condensed via ambient air and recycled as coolant for the fuel cell stack. The remaining steam portion is diverted to the fuel processor to meet the fuel processor's steam needs. Accordingly, heat from the fuel processor and combustor

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can then be devoted entirely to superheating the steam, and in some cases the fuel and air inputs to a primary reactor.

**[0006]** In one embodiment, the present invention results in a significant reduction in the air needed by an auto-thermal reformer (ATR) based fuel processor because the feed streams are hotter than in prior art fuel cell systems due to preheating via a heat exchange utilizing the steam exiting the fuel cell stack. In this embodiment, less oxidation in the ATR based fuel processor is therefore required to meet a given outlet temperature. Accordingly, the fuel processor efficiency is increased. Furthermore, providing a sufficient steam to fuel carbon ratio (S:C) makes it possible to eliminate a partial oxidation (PrOx) reactor or a pressure-swing adsorption (PSA) device from the fuel processor, increasing fuel processor efficiency and decreasing fuel processor size and complexity.

**[0007]** Although the present invention is not limited to specific advantages or functionality, it is noted that the present invention increases fuel processor net efficiency for a given operational constraint. The present invention permits the ability to use higher S:C ratios thereby potentially reducing the size and cost of the primary reactor and water gas shift (WGS) reactors. It is also noted that the present invention improves the transient performance via improved steam availability.

**[0008]** In one embodiment, a fuel processor based fuel cell system is provided comprising a primary reactor adapted to generate a gaseous reformat from feed inputs. The feed inputs

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comprise steam. The system further includes a high temperature proton exchange membrane fuel cell (HT-PEMFC) stack in fluid communication with the primary reactor. The HT-PEMFC stack is adapted to receive the gaseous reformat for generating electrical power and to generate the steam needed for the primary reactor.

**[0009]** In another embodiment, a fuel processor based fuel cell system is provided comprising a reactant stream having steam, a primary reactor adapted to generate a gaseous reformat using the reactant stream, and a primary reactor heat exchanger in fluid communication with the primary reactor to preheat the reactant stream. The system also includes a high temperature proton exchange membrane fuel cell (HT-PEMFC) stack adapted to receive the gaseous reformat for generating electrical power. The HT-PEMFC stack is cooled by water and the steam is provided via water vaporization in the HT-PEMFC stack. The system further includes a catalytic combustor, and a superheat heat exchanger adapted to receive heat energy from the catalytic combustor to provide additional preheating to the reactant stream before being used in the primary reactor.

**[0010]** In still another embodiment, a fuel processor based fuel cell system is provided comprising a reactant stream having steam, and a primary reactor adapted to generate a gaseous reformat using the reactant stream. The system also includes a high temperature proton exchange membrane fuel cell (HT-PEMFC) stack adapted to receive the gaseous reformat for generating electrical power. The HT-PEMFC stack is cooled by water and the steam is provided via water vaporization in the HT-PEMFC stack. A water gas shift (WGS) reactor is in fluid

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communication between the primary reactor and the HT-PEMFC stack, and a primary reactor heat exchanger is situated between the primary reactor and the WGS reactor to preheat the reactant stream. The system further includes a catalytic combustor, and a superheat heat exchanger adapted to receive heat energy from the catalytic combustor to provide additional preheating to the reactant stream before being used in the primary reactor.

[0011] These and other features and advantages of the invention will be more fully understood from the following description of a preferred embodiment of the invention taken together with the accompanying drawings. It is noted that the scope of the claims is defined by the recitations therein and not by the specific discussion of features and advantages set forth in the present description.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The following detailed description of the embodiments of the present invention can be best understood when read in conjunction with the following drawings, where like structure is indicated with like reference numerals and in which:

[0013] FIG. 1 is an exemplary schematic diagram of one embodiment of the present invention;

[0014] FIG. 2 is a graph of a pinch analysis run on an embodiment of the present invention;  
and

[0015] FIG. 3 is a graph of a pinch analysis run on another embodiment of the present invention.

DETAILED DESCRIPTION OF THE EMBODIMENTS OF THE INVENTION

[0016] An exemplary schematic diagram of an embodiment of a fuel cell system **10** according to the present invention is shown by FIG. 1. The fuel cell system **10** includes a primary reactor **12** connected to a water gas shift (WGS) reactor **14**, which in turn feeds gaseous reformat to a high temperature proton exchange membrane fuel cell (HT-PEMFC) stack **16**. By “high temperature”, it is meant that the HT-PEMFC stack **16** has an operating range of about 100° C to about 150 °C. The primary reactor **12** in one embodiment is an auto-thermal reactor (ATR), which uses fuel, steam, and air as input streams to form the gaseous reformat. In another embodiment, the primary reactor **12** is a steam reformer (SR), which uses only fuel and steam as the input streams.

[0017] The HT-PEMFC stack **16** is a collection of fuel cells, which produces electricity by electrochemically combining hydrogen and oxygen to form water. The hydrogen is broken down into its components (protons and electrons) at an anode side **18** of each fuel cell which is represented collectively by one half of the HT-PEMFC stack **16**. From the anode side **18** the protons pass through an electrolyte **20** of each fuel cell to a cathode side **22**, which is also collectively represented by the other half of the HT-PEMFC stack **16**. The electrons, however, are forced to pass through an external circuit, thereby supplying electrical power to an external load **24**.

[0018] The oxygen needed at the cathode side **22** of the HT-PEMFC stack **16** is taken from air **26** that has been pressurized and humidified. The hydrogen required for the anode side **18** of the

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HT-PEMFC stack **16** is extracted from a hydrogen-containing fuel **28** in a process called reforming. In one embodiment, the fuel **28** is combined with compressed air **26** and steam **30**, via a mixing port **31**, into a reactant stream **32** which is superheated and then fed into the primary reactor **12**. In another embodiment, the fuel **28** is combined with the steam **30** to form the reactant stream **32** which is superheated and then combined with the compressed air **26** in the primary reactor **12**. In still another embodiment, the compressed air **26** is combined with the steam **30** to form the reactant stream **32** which is superheated and then combined with the fuel **28** in the primary reactor **12**. In yet another embodiment, the reactant stream **32** comprises only the steam **30** which is superheated and then combined with the compressed air **26** and the fuel **28** in the primary reactor **12**.

[0019] During the reforming process, the primary reactor **12** breaks down the reactant stream **32** into hydrogen-rich gaseous reformat **34** along with other byproducts. One particular byproduct is carbon monoxide (CO), which is harmful to the catalyst present in the HT-PEMFC stack **16**. Accordingly, CO is reduced and/or removed by feeding the gaseous reformat **34** directly into the water gas shift (WGS) reactor **14**, where the CO is converted into CO<sub>2</sub>. The reduced-CO gaseous reformat **36** is fed optionally into a final CO-polishing stage **38**, such as a partial oxidation (PrOx) reactor or a pressure swing absorber (PSA). Next, the gaseous reformat **36** is then fed into the anode side **18** of the HT-PEMFC stack **16** to provide hydrogen and humidification in order to produce electricity for load **24**.

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[0020] As illustrated in FIG. 1, a primary reactor heat exchanger (PRHX) **40** is situated between the primary reactor **12** and the WGS reactor **14** to preheat the reactant stream **32**. Additional preheating is provided to the reactant stream **32** through a superheat HX **42** exchanging heat from a catalytic combustor **44**. A WGS reactor heat exchanger (WGS HX) **46** that is provided between the WGS reactor **14** and HT-PEMFC stack **16** also provides the steam **30** an initial boost of heat energy before entering the PRHX **40** and superheater **42**.

[0021] It is to be appreciated that the primary and WGS reactors **12** and **14**, respectively, their respective heat exchangers **40** and **46**, and the optional final CO-polishing stage **38** represent collectively a fuel processor **47**. Furthermore, in the above-illustrated embodiment the present invention provides a new source for the generation of the steam **30** needed for the reforming process carried out in the primary reactor **12** of the fuel processor **47**. In one embodiment, steam **30** is provided via water vaporization of water **48** used as a coolant in the HT-PEMFC stack **16**. It is to be appreciated that water **48** may contain additives, such as glycols, and other chemicals which depress the freezing point of water.

[0022] Within the HT-PEMFC stack **16**, the water **48** is vaporized into a relatively large quantity of steam **30** in cooling channels (not shown) provided adjacent to the anode and cathode sides **18** and **22**, respectively, by the heat of the reaction. This large quantity of generated steam **30** is then divided into a first steam portion **30a** and a second steam portion **30b** by a steam diverter **49**. In one embodiment, the first steam portion **30a** is about two-thirds to about one-half of the vaporized water in the steam **30**, which is recondensed and recycled to the HT-PEMFC



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stack **16** for cooling needs. The second steam portion **30b** is the remaining third to one-half of the vaporized water in the steam **30**, which is diverted to the primary reactor **12** to meet the steam requirements of the reforming process.

[0023] With the above described embodiment, a substantial portion of the heat generated by the primary reactor **12** and combustor **44** is then devoted to superheating the reactant stream **32** comprising at least the second steam portion **30b**, and in some cases, air **26** and/or fuel **28**. In one embodiment utilizing an ATR as the primary reactor **12**, devoting more heat to superheating results in a significant reduction in the air **26** needed by the ATR. It is to be appreciated that less air **26** is needed in this embodiment because the liquid mixture **32** is then hotter, so that less oxidation inside the ATR is required to meet a given outlet temperature. Accordingly, a net increase in fuel processor efficiency is provided.

[0024] Because in all embodiments the HT-PEMFC stack **16** operates at a higher temperature than prior art PEMFC stacks, additional heat recovery is also provided by anode and cathode condensers **50** and **52**, respectively, as well as with a stack excess steam condenser **54**. The steam condenser **54** is used to recondense the first steam portion **30a**. Additionally, because not all of the hydrogen in the gaseous reformat **36** is consumed in the HT-PEMFC stack **16**, anode exhaust **56** containing excess hydrogen is fed into the combustor **44** to maintain the temperature required for the reforming process. Before entering into the combustor **44**, the anode exhaust **56** is preheated by an anode exhaust preheat HX **58**, as well as the air **61** used in the combustor **44** by a combustor air preheat HX **60**. As illustrated, exhaust **62** of the combustor **44** provides the

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heat input to the superheat HX **42**, the anode exhaust preheat HX **58**, and the combustor air preheat HX **60** before exiting to ambient.

[0025] Water **48** is also recovered from anode and cathode exhausts **56** and **57**, respectively, to maintain the necessary water supply to the primary reactor **12**. Anode and cathode exhaust liquid separators **64** and **66** are provided for this purpose, supplying water **68** to a coolant tank **70**. It is to be appreciated that the anode and cathode exhaust liquid separators **64** and **66**, respectively, remove enough water from the anode exhaust **56** and the cathode exhaust **57** exiting the HT-PEMFC stack **16** to make the fuel cell system **10** water neutral. A stack coolant liquid separator **72** is also provided to separate the liquid water **48** from the steam **30** exiting the HT-PEMFC stack **16**, wherein the liquid water **48** from the separator **72** is returned to the coolant tank **70**.

[0026] As mentioned previously, the first steam portion **30a** is recondensed in the stack excess steam condenser **54**, wherein its condensate **74** is received by the coolant tank **70**. Heated air **76** used to condense the first steam portion **30a** is first preheated by the anode and cathode condensers **50** and **52**, respectively. The heated air **76** exiting the cathode condenser **52** will be heated towards the two-phase temperature of water (about 100° C). After exiting the steam condenser **54**, a portion of the heated air **76** is then pulled into a compressor **78**, such as through an access port **77**, with excess heated air exiting to ambient.

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[0027] As illustrated, the compressor **78** feeds the cathode side **22** of the HT-PEMFC stack **16** and the primary reactor **12** with portions of heated compressed air **26** through an air diverter **79**. This feed arrangement of compressed air **26** minimizes the possibility that the water **48** will recondense in the inlet of the HT-PEMFC stack **16**. In addition, in the embodiment where the compressed air **26** is provided as part of the reactant stream **32**, supplying heated compressed air **26** will minimize the possibility that the water **48** will recondense in the inlet of the PRHX **40**.

[0028] In still other embodiments, alternative component arrangements are useful for system startup. For example, a bypass circuit **80** is used to divert the gaseous reformat **36** into the anode exhaust preheat HX **58** to provide greater heat input to the anode exhaust **56** at startup before sending the gaseous reformat to the HT-PEMFC stack **16**. In still another embodiment, a water injector **82** is used to put water into the reactant stream **32** prior to entering into superheat HX **42**. This injected water flashes to steam in the superheat HX **42** in order to provide the required steam for the primary reactor **12** at startup.

[0029] With reference to FIGS. 2 and 3, a pinch analysis was performed to estimate the potential increase in fuel processor efficiency. In particular, FIG. 2 is a plot of fuel processor net efficiency which is defined as hydrogen power consumed in the HT-PEMFC stack **16** divided by the fuel energy consumed in the primary reactor **12** based on a system with an anode stoichiometry of 1.2. The results for a fuel cell system having stack heating (Q) according to the present invention i.e., use of the second steam portion **30b** as a steam source for the primary reactor **12**, are plotted as square symbols. The results for a fuel cell system not having stack

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heating i.e., all steam **30** is recondensed and returned to coolant tank **70** and steam is provided via alternative means, are plotted as diamond symbols.

[0030] As illustrated by FIG. 2, for all “No Stack Q” points with net efficiency below 76%, the pinch temperature (T) is about 50° C. For all “With Stack Q” points, pinch temperatures are above 680° C. The results of the pinch analysis for the embodiment of FIG. 2 indicates that with no stack heating such as with conventional fuel cell systems, the best efficiency achievable is about 79.9% with a ratio of steam to fuel carbon (S:C) equal to about 2.4. With stack heating provided in accordance with the present invention, however, the efficiencies achievable are according to Table 1.

Table 1

<u>% Efficiency</u>	<u>S:C</u>
81.3	4.4
81.1	4
80.9	3.6
80.6	3.2
80.4	2.8
79.9	2.4

[0031] FIG. 3 is a similar plot to that of FIG. 2 but for a system with anode stoichiometry of 1.1. For all “No Stack Q” points, the pinch temperature is 50° C. For all “With Stack Q” points, pinch temperatures are above 700° C. The results of the pinch analysis for the embodiment of FIG. 3 indicates that with no stack heating such as with conventional fuel cell systems, the best efficiency achievable is about 81.9% with a S:C ratio equal to about 2.0. However, with stack

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heating in accordance with the present invention the best efficiency is about 87.8% with a S:C ratio equal to about 4.4, and even with a S:C ratio equal to about 2.0, efficiency is about 86.0%.

[0032] It can be seen from the plots of FIGS. 2 and 3 that integrating stack heat via water vaporization significantly increases net fuel processor efficiency. Furthermore, integrating stack heat via water vaporization enables a broader range of S:C operation while maintaining a relatively high efficiency. It is envisioned that using a higher S:C ratio may be preferable to reduce the size and cost of the primary and WGS reactors **12** and **14**, respectively. Further, it is envisioned that using a higher S:C ratio may decrease or eliminate the need for providing both the final CO-polishing stage **38** and additional stack humidification.

[0033] It is to be appreciated that the efficiency gain in the present invention is realized by incorporating heat from the HT-PEMFC stack **16** into the primary reactor **12**. Heat from the gaseous reformat **34** and combustor **44**, which had previously been used for steam generation in conventional fuel cell system, is now used to superheat the reactant stream **32**. In one embodiment which uses an ATR for the primary reactor **12**, this higher preheating of the reactant stream **32** results in significantly lower requirements for compressed air **26**. For example, in the embodiment having the anode stoic equal to 1.1 (Figure 3) the ratio of atomic oxygen in air flow to carbon in fuel flow (O:C) increases nearly linearly from about 1.0 to about 1.5 as the S:C ratio is increased from about 2 to about 4.4 for the example without stack heat integration, but is fairly steady between about 0.75 and about 0.8 for the embodiment with stack heat integration. This

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lower fuel processor air requirement reduces the size, cost, and parasitic energy consumption of the moving hardware of the compressor **78**.

**[0034]** The levels of efficiency obtained via stack heat integration (particularly with anode stoic of 1.1) not only surpass those of conventional ATR-based fuel processors, but also that of similarly pressurized steam-reformer based fuel processors. The values are similar to very high-pressure (10 to 20 bar) steam reformer based fuel processor systems, but retain the advantages of ATR-based fuel processors such as, for example, lower mass and volume, faster startup, better transients, and lower capital costs.

**[0035]** In addition to enhanced steady-state efficiency, the fuel cell system **10** of the present invention aids in fuel processor transients. For example, in a conventional fuel processor if a step change in power from 50% to 100% is requested, a lag of several seconds (often up to one minute) is typical in order for the additional steam generation to be established. This lag in steam generation typically makes such conventional systems have to either accept much higher CO during this period or limit the rate of power change. However, because excess steam **30** is generated by the HT-PEMFC stack **16** in the fuel cell system **10**, in an up-transient state, all steam **30** in one embodiment is diverted, via adjusting steam diverter **49**, to the primary reactor **12** until the lag of the system is overcome and/or the system reached its new steady state. The ability to control the relative portion of stack generated steam **30** to the primary reactor **12** via diverter **49** also leads to better CO control and the ability to double or triple power in a step-wise fashion.

**[0036]** As described above, the fuel processor-based fuel cell system **10** uses water as a two-phase stack coolant (liquid and steam) and draws a portion of generated steam for use in the fuel processor **47**, thereby resulting in a significantly improved system steady-state efficiency and transient response. Preferably, in one embodiment, the fuel cell system **10** uses a S:C ratio in the primary reactor **12** of about 2 to about 5, and most preferably in another embodiment a S:C ratio of about 3 to about 4 to minimize the size and cost of the WGS reactor **14** and to minimize or eliminate the need for the final CO polishing stage **38**.

**[0037]** Depending on the humidity required by the HT-PEMFC stack **16**, the fuel processor **47** can provide significant stack humidification, for example, about 20 to about 25% of the total relative humidity based on stack outlet conditions. In addition, if no humidification is desired, in another embodiment the water content can be removed from the gaseous reformat **36** before entering the HT-PEMFC stack **16** by directing the gaseous reformat via a bypass valve **84** to a separator **86** provided between the HT-PEMFC stack **16** and fuel processor **47**. The bypass valve **84** may also be used to service the bypass circuit **80** to divert the gaseous reformat **36** into the anode exhaust preheat HX **58** to provide greater heat input to the anode exhaust **56** at startup.

**[0038]** While the invention has been described by reference to certain preferred embodiments, it should be understood that numerous changes could be made within the spirit and scope of the inventive concepts described. Accordingly, it is intended that the invention not be limited to the

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disclosed embodiments, but that it have the full scope permitted by the language of the following claims.

We claim: